THE NATURE OF SCIENCE & OTHER LECTURES

by Edwin Hubble

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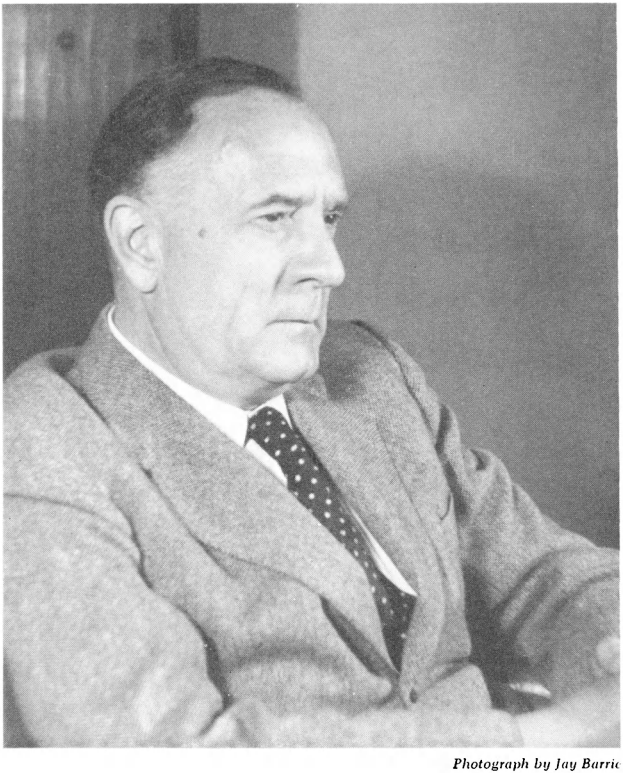

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EDWIN HUBBLE

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BY EDWIN HUBBLE

1954

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EDWIN HUBBLE 1889-1953

The contents of this book, hitherto unpublished, have been selected from the author's nonscientific writings. His scientific bibliography is of great extent. Among his published lectures are the Silliman Lectures at Yale, *The Realm of the Nebulae*; the Halley Lecture, *Red Shifts in the Spectra of Nebulae*; and the Rhodes Memorial Lectures at Oxford, *The Observational Approach to Cosmology*.

The lectures included in this book are divided into two groups. The first two in Part I were selected from the unpublished Hitchcock Lectures given at the University of California in 1948, and the third was the Commencement Address at the California Institute of Technology in 1938.

Similarly, Part II includes three addresses. The first, "O'er the Ramparts We Watch," was delivered on Armistice Day, November 11, 1941, a few weeks before Pearl Harbor, December 7. The second, dealing with war service (for which he was given the highest award of the United States Government for civilians, the Medal for Merit), was delivered at the Sunset Club of Los Angeles in 1946, and the third at a Los Angeles Town Hall meeting in the same year.

In his own field, Plaskett, the holder of the Savilian Chair of Astronomy at Oxford, has spoken of him as "one of the great astronomers of all time." Although

astronomy was the paramount and absorbing interest in his life, he had interests in many other fields—history, the classics, philosophy, the history of science, archaeology. Yet no description, however brief, could omit his deep love of nature or his skill as a dry-fly fisherman. This pursuit he described as "to follow a stream, to conform to a ritual, lastly, to catch a fish."

The knowledge which included in its scope books, manuscripts, paintings, and gardens, made him a valued Trustee of the Henry E. Huntington Library and Art Gallery from 1938 to 1953. And the publication of these lectures in his memory has been made possible by the Trustees and the Friends of the Huntington Library.

G. H.

PART I

FISHING IN COLORADO

THE NATURE OF SCIENCE

The history of modern science began with the Renaissance. It developed slowly at first, then faster and ever faster, until it now threatens to dominate our civilization. The general acceptance of the validity of science is a very recent phenomenon. As late as 1880, Huxley complained that "no reply to a troublesome argument tells so well as calling its author a 'mere scientific specialist.'" Fifty years later, Belloc complained that "a thing having been said to be established scientifically, there is no questioning of it." Today the attitude of the public is even more "advanced" (to use a dubious adjective). There are many who assume that the powers of science are unlimited, and some who refuse to believe a scientist who says that such and such a thing in his field is impossible.

All of these attitudes reflect a widespread misunderstanding of the nature of science and, consequently, of its limitations as well as its capacities. Scientists are well aware of this confusion as, indeed, are all men with a good liberal education. But these men seldom discuss the matter in public, and when they do, they rarely reach any considerable audience.

In the past, this reticence was understandable and perhaps even commendable. Scientists in general are not very articulate; they work in comparative seclusion and they do not cultivate the art of persuasion. But now a new era has emerged, and reticence is no longer a virtue.

Knowledge has been accumulating at an ever increasing rate, and knowledge, once it is available, can be used for evil as well as for good. It was inevitable that a day would come when the expanding body of knowledge would sweep across the danger level. That day, as you know, has come—and passed. Knowledge is already available by means of which men could wreck the civilization of the world—and the growth of knowledge continues faster than ever before.

It is imperative, in our day, that the applications of knowledge be controlled, and controlled not in one nation alone but throughout the world. This problem is the central problem of our time. A wise solution, enforced, will be the greatest landmark in the history of the human race. If no solution is found, there may be no more history.

The discussion of this paramount problem and its solution should be carried on with a clear understanding of the nature of science and of its applications. Statesmen and citizens alike should use the same language and understand what it is they are saying. Otherwise, the beneficial applications of knowledge may be suppressed along with the dangerous applications, that is, the baby may be thrown out with the bath; or, what is even more important, science may be confused with the applications, and to use another well-worn metaphor, the goose may be killed which lays the golden eggs.

It is for this reason that the scientists are beginning to talk more freely than hitherto. They speak rather haltingly, to be sure, and somewhat diffidently, but they are driven by a sense of urgency. The subject must be clarified, and those who actually practice the discipline should be able to speak with some authority. What they have to

say is not entirely new. A few men, including an occasional scientist, have explained the subject fairly well. But others have written nonsense, and the people, if they can, are left painfully to distinguish the good from the bad.

So the scientists are beginning to talk. They will not all say the same things, they will not necessarily agree on details, but if a sufficient number raise their voices, the essential features of the discipline will emerge rather clearly. This clarification of the problem which overshadows our civilization is the first duty of the scientists. The solution of the problem, and its enforcement, are the responsibility of all men—including the scientists, but only in their position as human beings, not as specialists.

For myself, I speak as a student of Astronomy, the type specimen of pure science. It is the oldest of the special disciplines, and it is called the mother of them all. The first notions of law and order in the universe were found in the heavens. When the same ideas were dragged down from the skies to the earth, Physics was born, and then, one by one, the other disciplines followed. But all of the brood were reared in the midst of human society, and all were exposed to the contamination of human desires. The old mother still remained remote and serene, the purest of them all. It is true that certain practical applications of astronomy were devised—timekeeping, navigation, and geography—but these specialties have long since been reduced to routine techniques, and removed from the body of the discipline.

It was not until recently, with the development of spectrum analysis, that this isolation was invaded. Today we look on stars and nebulae as so many celestial laboratories in which atoms can be studied under conditions of

temperature and density that far transcend the utmost limits of terrestrial equipment. In the same spirit, the exploration of space may be described as the study of matter and radiation on the grand scale, as distinguished from small-scale studies on the earth. Physics and Astronomy are merging. The first born has come of age, and, indeed, has become head of the family.

There is a unity in science, connecting all its various fields. Men attempt to understand the universe, and they will follow clues which excite their curiosity wherever the clues may lead.

But admitting these interrelations, astronomy may still be regarded as the purest of the special disciplines, the farthest removed from practical problems of daily life, and within this field we can most readily identify the essential features of science in general.

These features are not mentioned in the dictionaries. There you will find a wide range of definitions of science, and they emphasize the confusion in the language of general discourse. No adequate definition of the word has ever been formulated. The remark of the astronomer is perhaps as good as any of the attempts: "equipped with his five senses, man explores the universe around him and calls the adventure science." It is science in this sense that I propose to discuss—the acquisition of objective knowledge concerning the structure and behavior of the physical universe.

Let me begin with an attempt to emphasize the distinction between science and values, a distinction which is evident in a comparison, for instance, of the laws of motion and the canons of art. The realm of science is the public domain of positive knowledge. The world of

values is the private domain of personal convictions. These two realms, together, form the universe in which we spend our lives; they do not overlap.

Positive, objective knowledge is public property. It can be transmitted directly from one person to another, it can be pooled, and it can be passed on from one generation to the next. Consequently, knowledge accumulates through the ages, each generation adding its contribution.

Values are quite different. By values, I mean the standards by which we judge the significance of life. The meaning of good and evil, of joy and sorrow, of beauty, justice, success—all these are purely private convictions, and they constitute our store of wisdom. They are peculiar to the individual, and no methods exist by which universal agreement can be obtained. Therefore, wisdom cannot be readily transmitted from person to person, and there is no great accumulation through the ages. Each man starts from scratch and acquires his own wisdom from his own experience. About all that can be done in the way of communication is to expose others to vicarious experience in the hope of a favorable response.

The distinction between knowledge and wisdom is fully recognized in our time but it was not always so. Men wanted to explore the universe in all its aspects. The attempts began long ago. There was much fumbling; there were many false leads and occasional breath-taking achievements. Eventually it was realized that only one aspect—the world of positive knowledge—could be explored with confidence and, moreover, that success in the venture was measured in terms of disinterested curiosity. Special methods for handling the particular kind

of subject matter were developed under the leadership of Galileo and Newton, and modern science was launched upon its extraordinary career.

The requirement of disinterested curiosity was never formulated consciously. Yet it seems to have been the dominant motive in the work of all the great men of science. It has inspired the statement that the essential characteristic of science is the simple idea of attempting "to ascertain objective truth without regard to personal desires."

Men of science, like all other men, spend most of their lives in the larger world of values. There they play their roles as citizens and as human beings. But occasionally they slip out of the circle into another world that knows nothing of values. There they attempt to explore the universe as it is—not as it should be, but as it is. They may not always achieve complete detachment, yet that is their conscious aim. Driven by sheer curiosity, they seek to understand the world—not to control it, not to reform it, merely to understand it. This approach has been extraordinarily successful within a limited field—the field of science. There seems to be no competing attitude in the exploration of new fields of positive knowledge.

The subject matter of science has been described as "judgments on which it is possible to obtain universal agreement." These judgments do not concern individual events, which can be witnessed only by a few persons at most. They are the invariable association of events or properties which are known as the laws of science. Agreement is obtained by observation and experiment—a court of appeal to which men of all races and creeds must submit if they wish to survive.

If anyone refuses to agree with a judgment, we ask

him to go and test it for himself. If he still refuses to concur, we ignore his words and watch his actions. There is a story of Simon Newcomb which illustrates the point. A crank rushed into his office one day (Newcomb was Superintendent of the *Nautical Almanac* at the time) and announced belligerently that he did not believe in the law of gravity. Newcomb did not argue the matter; he merely invited the fellow to jump out of the window, and then watched to see what would happen.

The laws of science are derived from, as well as tested by, observation and experiment, and especially from measurement. The measures can never be exact in the absolute sense, and this margin of error must be taken into account in all interpretations of the data. The difficulty is met and overcome by the use of "probable errors," a conception that is peculiar to science. At every stage of an investigation, the uncertainty of each measure and each combination of measures is carefully estimated, and expressed numerically. For instance, a particular measurement is repeated many times and the average of all the results is adopted as the most probable value. Then, from an analysis of the differences in the individual measures, it is possible to say that the error in the adopted mean value has an even chance of being less than, or greater than, a certain quantity. This quantity is called the "probable error."

The conception, as I said, is peculiar to science. It has no place in the world of values. Bertrand Russell has discussed the distinction in his best epigrammatic style. After remarking that subjective certainty is inversely proportional to objective certainty, that we are most certain of those judgments we cannot demonstrate, he reminds us that when a scientist has determined a quantity with un-

usual accuracy, he is the first to admit that he is likely to be wrong—and he knows about how wrong he is likely to be. And Russell then asks the question, "Who ever heard a theologian preface his creed, or a politician conclude his speech with an estimate of the probable error of his opinion?" These remarks emphasize the fact that science deals with probable knowledge and that the methods of science are adjusted to their proper subject matter; also, they call attention to the fact that a scientist never attempts to speak with personal authority in his field, but merely demonstrates conclusions which anyone (in principle) may verify if he cares to take the trouble.

The laws which are the subject matter of science take many forms, ranging from simple definitions—such as the invariable association of properties which identify, for example, the element of iron—to very complicated associations of events such as the law of falling bodies. However, they are all quite general statements, and they apply to numerous actual or possible cases. The term "invariable" represents an assumption. If an association is observed to hold in many cases of a particular kind, it is assumed that the same association will be found in the next case that will be observed in the future. In carefully controlled experiments the number of test cases may be reduced to a minimum, and occasionally to a single critical trial. The results are confidently stated as laws, merely because they fit into the general pattern of knowledge within the particular field which is based upon innumerable data. Nevertheless, they represent probabilities only. The sun has risen each day in the past. It will probably rise tomorrow, as everyone agrees.

The nature of the subject matter defines the realm of

science. The necessity for general agreement restricts the explorations to the field of positive knowledge, and this knowledge concerns not ultimate reality, but phenomena only.

The methods of science may be described as the discovery of laws, the explanation of laws by theories, and the testing of theories by new observations. A good analogy is that of the jigsaw puzzle, for which the laws are the individual pieces, the theories local patterns suggested by a few pieces, and the tests the completion of these patterns with pieces previously unconsidered. Following this analogy, just as local theories are built up from pieces, so general theories are built up from local theories. The scientist likes to fancy, although he cannot demonstrate, that sufficient pieces may be assembled to indicate eventually the entire pattern of the puzzle, and thus to reveal the structure and behavior of the physical universe as it appears to man. At any rate, he has found methods which, when restricted to their proper fields, have been constantly advancing in the desired direction. He is bound to continue the explorations unless or until he runs into a blank wall of self-contradictions.

The laws of science are almost innumerable, but they fall into relatively few general types. The discovery of a new type is a notable event in the progress of science, but once the type is established, lesser men can add individual examples at a rate measured largely by patience and industry.

The laws derived from observation and experiment are discoveries in the true sense of that word, and a new type generally opens to investigation a previously unexplored field of knowledge. Nevertheless, the laws are the subject matter of science; they are not the finished

composition. It is theory that integrates the laws, and the making of successful theories is a creative activity whose operation is difficult to understand.

Science is pragmatic. Theories are judged by a single criterion—do they work? Their origin does not matter. They may be inferred, or invented, or dreamed. Until they are tested they are merely working hypotheses; in other words, they are plausible interpretations of data already available. Ingenious men can and do invent many theories to account for a given set of data.

Historians play this game endlessly. Froude remarked eighty years ago that "facts of history are like the letters of the alphabet—you may make them spell what you like." But scientists do not enjoy the same freedom. Each theory, while accounting for the laws already known, predicts new, hitherto unobserved laws. Therefore, the theories of scientists, unlike those of the historian, can be tested by observation and experiment in new fields. And the tests are made. The validity of theories is measured, not by their origins but by the verification of predictions. This procedure is the very essence of the scientific method, and serves to control the powerful but dangerous instrument of inductive reasoning. When theories cannot be tested, their appeal is largely aesthetic.

In these circumstances, the making of theories is a measure of men. A few seem to have a flair for inventing the right kind of theories—the kind that survive the tests, at least for a time. But the majority of men, however ingenious, are handicapped by the inevitable tests.

This feature of theory-making is especially prevalent among theories on the higher levels—among the great generalizations which correlate previously isolated theories and furnish the pattern for very large tracts of

knowledge. Universal gravitation waited for a Newton; relativity, for an Einstein.

But even the best of theories are accepted as temporary working hypotheses. The laws of science are relatively permanent, but the theories, which attempt to explain the laws, come and go. They serve their days of usefulness and then they fade away. We know only a little part of the universe, and our knowledge is constantly expanding. We predict what to expect in the new regions, from the information we already possess. When the actual data are found and reported, the theories are always reviewed in the light of the new information. Inconsistencies are pounced upon eagerly because they often point the way to new and broader conceptions. Current theories are discarded, or they are revised or merged into a wider generalization, and the event is welcomed as another step toward the ultimate goal. Such events occur frequently on the low levels of theory when, for instance, the first explorations are rapidly pushed out into newly opened fields. But on the top levels they are rare, as, for instance, when Newtonian gravitation was absorbed into the deeper, more inclusive theory of relativity.

The openings of new fields are exciting periods, and then the methods of science are rather clearly seen. It is like a campaign. Accumulating knowledge piles up at some barrier beyond which lies unknown darkness, the land that challenges the explorer, where, he likes to imagine, almost anything is more than likely to happen. A day comes when a weak spot is found in the barrier, often by chance. Immediately, a breakthrough is engineered, hammered out by every means available. Once the break is made, explorations sweep forward like a flood spreading out until it is stopped by more distant

barriers. This first sweep is a reconnaissance of the field, guided by the general knowledge already at hand. Next comes the consolidation of the new country—the careful surveys, the accumulation of new laws, the review of old theories, and, perhaps, the formulation of new theories. Finally, when order is established, the territory is integrated into the main body of knowledge, and theory is reviewed on the high levels.

In principle, the development of a new branch of science begins with observations and simple experiments. The results are reported in terms of measured quantities together with the estimated uncertainties of the measures. These data furnish a growing body of laws which represent the actual subject material. When a sufficient number of laws is assembled, the creation of theories begins. Various laws are grouped together as special cases of a general principle or theory. The work starts tentatively, guided perhaps by analogies in other fields and by a working hypothesis called the uniformity of nature. Most of the theories fail to meet the tests of predictions, but with the accumulating experience of trial and error, men begin to get the feel of the data. A confident, sure touch is developed, and the game becomes exciting. Theorizing on the higher levels follows much the same pattern, until finally the new branch is merged into the general body of science.

These procedures are based on inductive reasoning. From a few scattered cases, we infer a general principle that should apply to all similar cases. The validity of induction has never been demonstrated. It remains as an unsolved problem of logic. Consequently, the theories of science, as well as the measurements, must be accepted on the basis of probabilities. When a theory collapses, an

attempt is made to replace it with a more probable theory, and, in this way, science proceeds as a series of successive approximations.

When a sufficient body of high-level theories has been assembled, an entirely new chapter is opened. An attempt is made to derive from the theories a limited set of general principles whose implications cover the entire branch, just as Euclid's axioms were once supposed to contain implicitly the whole of plane geometry. If such an attempt were ever successful, and the chosen set of principles did close and bound the field, that branch of science would be perfected and written off the programs of the explorers. For then the reasoning would be purely deductive, and the ramifications of the field could be confidently predicted without recourse to further observations. Science could then be taught as elementary geometry is taught.

This pleasant speculation suggests the intimate relation between science and mathematics. They are not at all the same thing. Mathematics is not science, although it furnishes the scientist with some extremely powerful tools for the analysis of data and the handling of theories, especially on the higher levels. But mathematics is akin to pure logic. It concerns relations between postulates. Russell, in another happy epigram, has said that the mathematician never knows whether what he is talking about is true, and wouldn't be interested if he did. Haldane once remarked that mathematics deals with "possible worlds," that is, with logically consistent systems, and is not interested in any attribute except logical consistency. Following this lead, it might be said that mathematics furnishes us with a vast array of "possible universes," and that science attempts to identify, among them, the actual universe

that we inhabit. The acquisition of new knowledge is constantly reducing the list of possible universes which must contain our own. It is the task of theoretical, or mathematical, physics to keep us informed as to the minimum number, and to indicate critical tests by which the list may be still further reduced.

A conspicuous example of this procedure is found in cosmology, a study which concerns the gross, large-scale features of the physical universe. The combined efforts of mathematical physicists and observers have reduced the array of possible universes to such a limited range that it is now possible to predict with confidence that the type of the actual universe will be identified within the foreseeable future, perhaps within the next decade.

The mathematical physicists are constantly studying the general principles of nature, derived by induction, as though they were postulates which close and bound the fields of science. In the end, the set of postulates must be complete and must be logically consistent. The occasional recognition of inconsistencies has led to reinterpretations of large areas of knowledge, and even to such a major revolution in scientific thought as the theory of relativity.

A set of postulates derived from observations will probably be incomplete; it is unlikely that we know as yet all of the fundamental principles of nature. Theoreticians attempt to measure these gaps in the sets of postulates by the degree to which the field closed and bounded by the postulates fails to coincide with the observable universe. It is possible that new fundamental principles may be found in this way, but their validity must always be checked by observation.

This discussion of the nature of science began with the

simple observer, exploring the world about him, and has now wandered into the fringe of theory and mathematical abstractions. If it followed a natural course, it would linger for a while in that field, and then conclude with a dissertation on the philosophy of science. I do not propose to follow this course, but I shall tell you a fable concerning the philosophical aspects of scientific research, before passing on to a summary of the ground that has been covered.

The fable is Eddington's tale of the fisherman—Eddington calls him an ichthyologist—and it will take its place as a classic in the literature of science. An ichthyologist set out to study fish in the ocean. He spent his time dipping a net with two-inch meshes into the water and studying the fish he caught. He made two discoveries, namely, all fish have gills and all fish are more than two inches long. These results represent empirical and *a priori* knowledge respectively. He could not predict the gills but he should have predicted the minimum length. In research, the fisherman's net is represented by the scientist's equipment—his tools, his sensory organs, and his brain which operates in certain patterns. A complete knowledge of this equipment, says Eddington, permits us to predict a large portion of the current body of knowledge—the *a priori* portion—without making a single experiment or observation. The remainder of the body of knowledge—the empirical portion—must be found by the explorers.

Eddington then proceeds to discuss the two kinds of knowledge, and satisfies himself that all of the important and significant knowledge is *a priori*, that even the fundamental constants of nature, from the gravitational constant to the rate of expansion of the universe, can be

derived within the study. The empirical knowledge, however curious and interesting, concerns mere trivial details in the scheme of things.

The problem illustrated by the tale of the fisherman is the central problem in the philosophy of science and the current discussions are highly controversial. Eddington's interpretation represents a minority point of view, but it is presented with such brilliance and persuasive power that it commands respect, if not concurrence.

The explorers are not deeply impressed by the controversy. They are pragmatists, and interpretations are useful only as long as they work, as long as they predict new phenomena and the predictions are verified. They know that in the past most of the really new fields have been opened by the explorers, using the methods of Galileo and Newton rather than the method of Plato. And they will continue their explorations on the assumption that, in the future as well as the past, new fields will be opened which cannot be predicted from the armchair.

From the foregoing descriptions and comments, it is seen that science is necessarily restricted to one aspect of the universe—the objective world of phenomena. It deals with probable knowledge only, its methods are empirical, its philosophy is pragmatic. The scientist explores the world of phenomena by successive approximations. He works in an atmosphere of probabilities; he knows that his data are never precise, and that his theories must always be tested. It is quite natural that he tends to develop healthy skepticism, suspended judgment, and disciplined imagination.

The world of pure values, that world which science cannot enter, has no concern whatsoever with probable knowledge. There finality—eternal, ultimate truth—is ear-

nestly sought. And sometimes, through the strangely compelling experience of mystical insight, a man knows beyond the shadow of a doubt, that he has been in touch with a reality that lies behind mere phenomena. He himself is completely convinced, but he cannot communicate the certainty. It is a private revelation. He may be right, but unless we share his ecstasy we cannot know.

SCIENCE AND TECHNOLOGY

In the first lecture we discussed the nature of science and its field of operation. To review it briefly—men attempt to explore the universe in all its aspects. Science is restricted to one aspect, the public domain of positive knowledge, where it is possible to obtain universal agreement on the subject matter. Methods have been developed for the purpose of handling the material, and, in so far as these methods have been restricted to this material, the explorations of science have been successful. But science by its very nature is barred from the world of values. Science operates in a strictly limited field which is utterly withdrawn from ideas of human worth and the public good. The scientist, in his purely scientific moods, seeks to understand the world—not to reform it, not to control it, but merely to understand it. The driving urge to research is sheer curiosity. And it is a fact, however strange it may seem, that when the scientist, being human, does not reach the heights of complete detachment, his success is measured largely by the degree to which his curiosity is disinterested.

There is no set procedure in research. Interest is aroused in a problem by a careful survey of a special field, by reports of new theories, by the acquisition of new tools, or even by chance. Some men keep their eyes on distant goals and consciously select problems which seem to lead in those directions. I, for instance, as an astronomer, am deeply interested in the possibility of inferring the nature

of the physical universe from the observed characteristics of the sample that can be studied, namely, the region of space that can be explored with telescopes. All roads which seem to lead in that direction attract me, and among them I try to select those which seem to be the most direct, and are amenable to the tools we possess. This inclination involves a considerable amount of planned research. Others may get their fun by investigating apparently isolated problems. Their response to problems is that of the Irishman at the fair: "Whenever you see a head, hit it."

Both approaches gain new knowledge, and it would be difficult to assess their relative efficiency. The reason is that when a piece of research is begun, we cannot predict what will be found. Otherwise it would not be research. Moreover, the explorations do not always proceed as planned. In the new country the explorer will come upon inviting bypaths which lure him away from what he originally considered to be the main trail. Most of them lead nowhere, yet time and again it has been one of these bypaths that has led to great discoveries of science—to knowledge of a wholly new kind, unimagined and hence unpredicted.

The explorations of bypaths play so great a part in any discussion involving the freedom of inquiry that a few cases should be mentioned as examples. The problem of selection is difficult because of the wealth of material. Important cases are found in the careers of almost all successful research men, and in the development of all the fields of science. In these days of nuclear physics, with all that it implies, the case of isotopes is probably as good as any. You are familiar with isotopes of uranium, and you doubtless know that the discovery of isotopes was an im-

portant step in the modern revolution of our conceptions of the structure of matter.

There were two previous steps, the discoveries of X-rays and of radioactivity which, together with that of isotopes, make a logical sequence of fundamental significance in the development of nuclear physics. All three of these discoveries were made, unexpectedly, by following the lure of bypaths. All three might easily have been missed if the discoverers had followed the main trails of their investigations.

In Germany, in 1895, Roentgen, working with a cathode-ray tube, happened to notice when he unpacked one of his barium screens, which had been packed in a cardboard box near the tube, that it was fluorescent, even though it had not been exposed to sunlight. This seemed very odd, because fluorescence was supposed to occur only after exposure to sunlight and to last only for a brief period following the exposure. Roentgen immediately set out to trace the fluorescing agent to its source, and finally discovered it in the cathode-ray tube. Furthermore, the radiation penetrated not only cardboard but even thin plates of metal, and affected not only fluorescent screens but photographic plates as well. Roentgen had discovered X-rays.

The announcement created general excitement in the laboratories over the world, and many physicists hastened to verify it by independent experiments. Becquerel followed up the verification by investigating the relation between X-ray emission and fluorescence—a logical procedure. He used uranium salts, which were known to be fluorescent, and after exposing the salt to sunlight, placed it on a photographic plate wrapped in black paper. When he developed the plate, he found an image of the salt

crystal. The investigation looked promising until one cloudy day when he could not make his salt fluoresce he found an image, just as usual. Here was an accidental bypath which, when followed up, led not to the relation between X-rays and fluorescence but to the discovery of the spontaneous disintegration of matter known as radioactivity. This happened in France in the year 1896.

The third step was taken in England in 1912. J. J. Thomson had discovered the electron and identified it as the carrier of the elementary, negative charge of electricity. The next step, quite logically, was to trace down the carrier of an elementary positive charge. He began by using an early form of what is now known as a mass spectrograph, and his final data were streaks on a photographic plate (they were called positive-ray parabolas) whose positions were determined by the atomic weights of the elements he was investigating.

Thomson's investigation proceeded smoothly and hopefully until he found double streaks for the gas neon. Here again, a bypath had opened up, not necessarily leading in the direction of the main trail. But this bypath, which, of course, was followed eagerly, led to the first recognition of an isotope. Neon, which was previously known as a simple chemical element with an atomic weight about 20.20, was now known to be a mixture of two elements, chemically identical, but with different atomic weights very close to the even numbers, 20 and 22. Such elements were called isotopes.

Today isotopes are known for most of the elements. The atomic table in its revised form has taken on a new significance, and already speculations are being made on the origin and evolution of the elements. From the point of view of applied science, it is of interest that all the iso-

topes have atomic weights close to whole numbers, and the small differences represent the binding forces—of one sort or another—that can be released and set to work.

Alert researchers are well aware of such possibilities, and they generally explore bypaths which stir their curiosity deeply. It is utterly impossible to follow each one to the end, including all the branches. In the selections that he makes, the researcher shows his worth.

These procedures are an essential part of the freedom of science. Too much planning and regimentation would stifle explorations in unknown fields for the specious benefits of greater efficiency in the fields already known. The researcher must follow his star. He will lay out a program, desirable in itself, and generally he will carry it through. But those bypaths are constantly in his mind, and the lure is irresistible.

These explorations have produced a large and growing body of knowledge concerning the physical world, and some of it has been put to practical use. The applications of knowledge, however, have no interest for the scientist as such, except perhaps as they may furnish him tools for still further explorations. Scientists, when functioning purely as scientists, are not at all concerned with the material benefits of mankind. They explore the world of phenomena in the same spirit as the artists explore the world of values—for their own inner satisfaction, and not for the good of society. Yet society supports them. Universities, foundations, and occasionally industry and government, support them—not perhaps in luxury, not often in the current style of the plumber and the bricklayer, but still they are supported. There are two reasons. The first reason is cultural. All men are curious. Knowledge stirs the imagination, and drives away the nightmares of super-

stition. Science has a place in a liberal education and has a part in contemporary culture.

The second reason for the support of scientists is practical. Long experience has shown that among the reports of pure scientists, something occasionally is found that may be put to practical use. The discoverers, in general, are not directly interested in the applications of their achievements. Usually, the possibilities are realized long after the discoveries are made—frequently, after the discoverers are dead. Yet it is a fact, and society recognizes it, that inventions are by-products of pure science. This statement, of course, refers to modern inventions in these days of modern science.

The scientist claims no distinction between the dignity of pure science and the dignity of its applications. Yet, if you press him closely, you are likely to arouse a quite unscientific gleam in his eye, and to hear him quote Sir Francis Bacon: "The contemplation of things as they are is, in itself, a nobler thing than a whole harvest of inventions." Only, of course, he may change the adjective "nobler" to "more profoundly satisfying" or even to "more amusing." And he may forget, in his lack of interest, that inventions are derived from such contemplation and from no other source.

The classical example of this relation between pure science and its application is the case of Faraday and the electrical industry. Michael Faraday's paramount interest was the nature of electricity and magnetism about which so little was known in his time. He studied the behavior of electric currents in magnetic fields until he established certain laws which, although they did not indicate the nature of either phenomenon, did lay a firm foundation for the field of modern electromagnetism. Years later, the

principles he formulated were put to practical use. A conductor moving in a magnetic field generated a current of electricity; a current sent through a conductor in a magnetic field, set the conductor in motion. Within a century there developed from these principles the vast electrical industry of today. Wherever we find a motor or a generator we may recognize a by-product of Faraday's disinterested explorations of a portion of the physical world.

Faraday might be called the complete scientist. As a poor young man, he accepted the position of laboratory assistant to Sir Humphry Davy, although Davy warned him that science was a mistress who paid badly. But, as Gladstone remarked, Faraday "deliberately made his calculation, gave up the butter, and settled down to worship the Goddess." He continued in this mind throughout the whole of his long and very successful career. "I have," he wrote in later life, "rather been desirous of discovering new facts and new relations dependent on magneto-electric induction than of exalting the force of those already obtained, being assured that the latter would find their full development hereafter." His assurance was justified but even without it, Faraday would have continued with his explorations.

Nevertheless, he was always ready to discuss problems with engineers and to lend a hand in settling a question of principle. For instance, Cyrus Field, when he was considering the project of the transatlantic cable, consulted Faraday, who at first doubted the possibility of getting a message across the ocean. Field immediately requested him to make all necessary experiments to settle the question, offering to pay him properly for his services. Faraday, refusing all compensation, investigated the problem until he satisfied himself that it could be done and gave

this assurance to Field. The project of the cable was then undertaken, but Faraday took no part in its engineering.

The same spirit—recognition of the possibilities of discoveries but lack of interest in their applications—was evident in his answers to a question frequently asked concerning his laboratory demonstrations of new principles, namely, "What is the use of it?" Benjamin Franklin, under similar circumstances, replied to a lady with another question, "What is the use of a new-born baby?" Faraday's answer was, "You may endeavor to put it to use," and on one occasion he is said to have answered a politician with the remark, "Some day you may be able to tax it."

Michael Faraday was a gentle, kindly man, and deeply religious. Yet his scientific explorations were made in an effort to understand the world—not to "control the forces of nature" and not to "benefit mankind."

This disinterested, impersonal approach must be accepted, understood, stressed, for in it seems to lie the only possibility of success within the field of pure science. But it is a difficult position for the public to accept. For one thing, it seems unlikely that men should expend time and thought and effort without looking for the rewards that would result in certain other fields of human activity. In these fields, a question that is asked often, perhaps too often, is "What is there in it for me?" As we have found, this point of view, from a worldly standpoint, does not occur to the scientist. This does not imply that he is morally superior; first, it is a matter of indifference, and second, it will not, as we have said, "get him anywhere." It is paradoxically true that "what there is in it for him" lies precisely in his avoidance of that very question.

Another source of confusion lies in the immense

amount of popular and superficial, sensational information to which we are exposed. To reach an approximation of judgment, the reader or listener must know the reputation among his fellow scientists of the man from whom the information emanates, and, what may confuse the issue further, what ability and integrity the reporter possesses to qualify him as an interpreter. In many instances the authority of the written word, so willingly taken for granted, is highly dubious or downright wrong. Contradictions follow, and the casual reader may experience a mood of excited interest or hopefulness, to be followed quickly by one of disillusionment, and finally of cynical skepticism. These might be expressed, after the fashion of our times, by two comic cartoons. In the first the reader says, "I don't have to worry about it. Let George do it." In the second he says, "Oh, it's all the bunk!"

But the chief difficulty is the confusing of the scientist with the engineer, and of science with technology. The general public knows little of science, but every hour of our lives is passed among the achievements of technology. Our entire material civilization is an achievement of technology. And yet, the two disciplines are quite distinct, as different as the careers of Michael Faraday and Thomas Edison. Science explores the world, and technology applies some of the results to the service of mankind. Technology is a by-product of science. Necessarily, it lags behind science. In the past it was far behind, but in more recent times, and especially under the impetus of war, it has been reducing the gap as rapidly as practical.

To reverse the method of the Baker in "The Hunting of the Snark," whose narrative skipped forty years, let us look back forty years. Motor cars were then successfully competing with horses. Airplanes were trying their

wings. Bleriot had just flown the English Channel, and the nations, in conference, were hurriedly examining the new problem of international boundaries. The wireless was groping its way over our earth. Marconi, that year, transmitted a message from Ireland to Buenos Aires, six thousand miles away.

There is no need to dwell upon the development of these new implications. The tremendous advances in technology during the intervening years are almost too familiar. They tend to distort perspective. Technology strides across the modern stage like some gigantic, streamlined god. Some, instinct with the spirit of craftsmanship, worship the machine for its very perfection. Others, fearing the reckless ignorance of mortals, nervously urge that the demon be exorcised.

But the development of technology, however impressive, does not represent the fundamental history of the last generation. In that year before the first World War we saw, if we had realized, vast industries in their beginnings. And more—for around us, if we could have recognized them, were the very germs of many vital factors in the technological culture of today. They existed as mere toys in the laboratories, by-products of pure research—here an amusing new correlation between phenomena, there an ingenious, experimental device for seeking new answers from nature. For behind technology is the ultimate source of inventions, and that source is pure science.

This relationship is the subject of the present discussion. The development of technology has produced dangers as well as benefits. The dangers are now so great that if ruthlessly used by evil men they may bring an end to civilization, and the word of the prophet will be brought to pass, that "without wisdom the people perish." These

dangers must be controlled, and the controls must be formulated with a clear understanding of the nature of both science and technology.

The progress of applied science has been accelerated by the organization of industrial laboratories. These were begun on a very modest scale, generally for developing processes, and were expanded until now they are called industrial research laboratories. Many of them surpass in equipment and convenience most of the laboratories of pure science.

Their astonishing growth is shown in certain bulletins of the National Research Council, which define industrial research as "the endeavor to learn how to apply scientific facts to the service of mankind." In 1920, a bulletin listed 297 companies in the United States which maintained such laboratories. By 1946, the list had grown to 2,443, and some of the companies or corporations maintained several laboratories—General Electric alone has about 20. These institutions employed a scientific personnel of nearly 55,000, in addition to about 35,000 others rated as technical personnel, and a somewhat larger number of non-technical persons. Such figures indicate the response of industry to a growing realization of the commercial possibilities buried in reports of scientific explorations.

In general, industrial laboratories are quite different from the workshops of pure research. They are devoted, not to disinterested explorations, but to the rapid and efficient solution of specific problems, almost necessarily by the use of fundamental principles already known. They are commercial ventures, and highly profitable, as their rapid growth bears witness. But in them, research is generally regimented and freedom of inquiry is cur-

tailed. The workers must keep to the main trail, must ignore the bypaths along the way.

Since the goals are clear and lie in country already explored, the problems can be attacked by the organized efforts of a team. In a typical case, the problem of the moment is analyzed into a number of component parts, each part is given to a separate group, and the set of part solutions, when they are found, is assembled in the main office to make a solution of the whole. This case is, properly speaking, development, or straightforward engineering, and represents the main function of the industrial laboratories of a generation ago—investigations made to find the optimum combination of known factors that would meet a given set of specifications for performance. Later on, individuals and groups were detailed to study various materials, machines, or principles in order to find new applications that would be of "service to mankind," and, incidentally, would be commercially profitable. Both of these activities, since they include the solution of immediate problems and lead to tangible results, can be immensely exciting. They appeal strongly to many men, and the appeal is readily understandable.

These men are engaged in applied science. It is as though they took their pleasures in solving problems by means of the calculus or searching for new problems which can be solved by the calculus without attempting to examine critically the calculus itself, while the pure scientists would find their interest in the calculus and not in its applications.

These organized efforts have been so successful, the achievements are so obvious and familiar that, as I have said, there is a tendency among the uninformed to

identify science with technology. As a result, suggestions are frequently made that all research should be organized in the same manner. It is this confusion that I have been attempting to clarify. Pure research functions best in an atmosphere of freedom of inquiry, and it has never been consistently successful in any other atmosphere.

The history of modern technology began with the inventor, working perhaps in his garret, and proceeded by way of organization to the great modern development laboratories. A more fundamental approach was introduced much later in the form of general studies of principles and materials in a search for possible applications. In some cases, the search ventured quite close to the borders of pure science, especially in those fields which were still empirical. The problem of alloys, for instance, was largely empirical, and the properties of new mixtures could not be predicted with confidence. It was the laboratories of applied science that furnished the bulk of the modern data, by making and testing innumerable mixtures in a search for new materials for engineers. A very few useful results from a long and tedious program represented a large return on the investment, and analysis of the body of data thus assembled advanced our understanding of alloys. Permalloy is a case in point, and certain glasses, including the glass used for modern reflecting telescopes.

Occasionally, a pure scientist has been taken into an industrial laboratory, partly to maintain liaison with developments in the general field. The practice is increasing somewhat cautiously, and today there are a few groups doing fundamental research within the industries themselves. The fields are those which are not widely exploited by universities and foundations, and, conse-

quently, those in which the companies must meet competition largely by their own efforts. Explorations of their own particular fields, within their own laboratories, they believe to be sound insurance. Men are selected for their interest in the particular field, but thereafter, freedom of inquiry is permitted to a very considerable degree.

One question that always arises is that of security—should the reports of explorations be kept as confidential, or be contributed to the public body of scientific information. Points of view differ, but the tendency seems to be toward unrestricted dissemination of scientific knowledge —free intercourse on the scientific level—while technological processes, until protected by patent, are guarded.

Engineering in industry has been offered as an example of applied science, because in that field the distinction is especially clear cut. Other fields would have served, but in some it is difficult to draw the line neatly. Medical research, for instance, is a border-line case. Research is directed toward an understanding of the human body, its normal behavior and its pathology. Practically all of the results are related directly to the benefit of human beings, and many of the programs are inspired by that motive. Nevertheless, the distinction is there, as in all fields—knowledge for the sake of knowledge, and the applications of knowledge for the service of mankind.

The distinction between the two activities has been pointed out very often but the relation between them has seldom been discussed. I have stated that applied science is a by-product of pure science, and the statement is logically correct. It has been suggested that the relation is one of symbiosis, that pure science supplies material for applied science, and that applied science, in turn, subsidizes pure research.

The arguments in support of this suggestion are rather thin. It is true that pure science does not subsidize itself —laboratories are philanthropic institutions—and that the funds by which they operate are derived ultimately from technological activities of one sort or another. But the major part of the funds comes from gifts by individuals or, in the case of state institutions, from appropriations by the states. Industry makes relatively little direct contribution to pure science, although it contributes generously to cerain fields of applied science, including among others, aeronautics, metallurgy, electric and chemical engineering.

The reason for this discrimination is very probably that directors must account for the distribution of the stockholders' money; investments can be made, but not gifts. The subsidy of pure science is a wise investment on the long view but a chancy gamble, practically a gift, on the short view. And, in general, "good business" is judged on the standards of the short view.

But industry, as distinguished from business, might well consider the long view. The case of Faraday and the electrical industry is an example. The history of progress in attempts to understand the structure of matter is equally significant. Each successive wave of new knowledge has brought in its train a new branch of engineering and a new major industry.

In the days when physics dealt with gross phenomena, and the molecule was the smallest known unit of matter, engineering was chiefly mechanical, and industry was chiefly a business of construction. However, there came a time when explorations penetrated the molecule, and isolated the atom. With the study of atoms, chemistry

matured, and was followed by chemical engineering and the modern chemical industry.

A century later, explorations penetrated the atom, and found swarms of electrons circling about central nuclei. For a while the nuclei remained recalcitrant, although the behavior of electrons could be studied with confidence. This phase led to electronic engineering, and, in industry, to the radio, radar, and television. Finally, the nuclei themselves were explored, and, out of this latest phase, we see developing before our eyes the beginnings of nuclear engineering, and the first steps toward an industry based on atomic power.

In the light of such history it would seem evident that industry should take the long view, and support in a substantial way pure, unregimented research within the general field of its special interests.

In this lecture we have described and illustrated the difference between pure science and technology, between the acquisition of knowledge and the application of knowledge, and we have emphasized the fact that technology is a by-product of pure research.

EXPERIMENT AND EXPERIENCE

Presently you will be transformed, somewhat miraculously, from students into graduates. You are leaving the formal garden of instruction, with its geometrical paths and its well trimmed hedges, and you are entering the open country. There you will find the topography rather confused; there you will select your own destinations, and you will seek your own approaches.

I do not know your thoughts as you await the final gesture but there is doubtless some awareness of time, of a dim procession of years rolling toward you. Some day you will look back, and you will see quite clearly the wake of those years. The old earth will be much the same, the same sun will shine by day, and the same stars by night. In short, the setting will remain unchanged but the action will have developed somewhat.

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The progress of science during the last generation has been described again and again, and the record transcends the descriptions. It was a period in which basic clues were found and exploited, in which entirely new fields were opened to exploration. Advances of the very first importance were made in almost every branch of research. Such phrases as the theory of relativity and the theory of the genes have become almost household terms.

The magnitude of the advance is impressive but the mere fact of progress is quite normal. Each one of the last

twenty-five centuries, at least, shows progress. During the last three centuries the development has been measured in generations, and recently, in decades. Science, by its very nature, is accumulative. The knowledge that comes from experiments is transmitted from person to person, from generation to generation, and each contributes to the growing structure. The meanest of research men stands on the shoulders of giants, begins where his predecessors halted.

This progress was not apparent in other activities. In 1910, we enjoyed a dubious sense of security. Suspicions had been lulled by a long period of peace and established order. The economic structure seemed to be stable. There was confidence in our government, pride in our independence. Almost every man believed he could better his condition by hard work and honest thrift; if he failed, he generally laid the blame on himself rather than on society. It seldom occurred to him that the world owed him a comfortable living. Life, we believed, was competitive and the role of the government was to insure fair play. The theory did not work perfectly—there was occasional corruption in high places, injustice, stupidity—but by and large society, like science, seemed progressive, and youth looked eagerly forward to a future full of promise.

Well, the years unrolled. Let us not be too superior about war. Our own nation was created by war, was enlarged by war, and was preserved by war. The armorer said, "All have the right to fight, none have the right to judge." You will doubtless see your wars, few generations escape that experience. Ours was on a grand scale, and it was followed by a great disillusionment. In a pageant of history, we watched empires crumble, economic structures collapse, societies disintegrate. We have seen gov-

ernments sacrifice their integrity, discourage in their citizens the ancient virtues of thrift and independence.

The story is long, and much of it, to me, is unsavory. For a moment, I use it merely as an illustration. There has been a marked change in the behavior of individuals and of societies; does the change represent progress? Some, as you know, say yes, that the old order included exploitation of the downtrodden masses, and that any change is good. Others say no, that the swing toward the totalitarian state suppresses that individual freedom of thought and action which is the very measure of civilization.

The conflict of opinion cannot be resolved by argument. Even though the factual evidence were agreed upon, and the logic of both parties correct, still the premises, the definitions of good and evil, of justice, and of desirable ends, would be irreconcilable. On both sides, the premises are asserted but they are not demonstrated. They cannot be demonstrated. The premises are in the nature of religious convictions. They are derived from authority, or from revelation, or from the inner conscience. Their validity is tested not by impersonal experiment, but by personal experience.

The premises are based upon values—standards by which we judge the significance of life. The meaning of good and evil, of joy and sorrow, of beauty, justice, success, all these are purely private convictions and they constitute our store of wisdom. They are peculiar to the individual, and no method exists by which universal agreement can be obtained. Consequently, there is no calculus of values, no ready transmission, no great accumulation through the centuries. Every man accumulates his own wisdom from his own experience.

The universe in which we live has two aspects. On the one hand is the realm of science, the public domain of positive knowledge. On the other hand is the world of values, the private domain of personal wisdom. Knowledge comes from observation and experiment; wisdom comes from personal experience.

The distinction is important and is not always clearly understood. The scientist, as other men, lives much of his life in the world of values, and there he may be great or small. But occasionally he slips out of the circle, into another realm that knows nothing of values. There he attempts to explore the universe as it is, or as it appears to him, uninfluenced by his own desires. The urge to pure science is disinterested curiosity. The research man does not necessarily seek to benefit mankind, he does not seek to reform the world; he seeks merely to understand the world.

The attempts began long ago with groping efforts that were scarcely conscious. There was much fumbling, many false leads, and occasional, breath-taking achievements. Finally, it was realized that progress was measured in terms of disinterested curiosity. A technique was developed under the leadership of Galileo and of Newton, and science entered its very successful, modern phase.

The success of the technique is emphasized by George Sarton:

"The saints of today are not necessarily more saintly than those of a thousand years ago; our artists are not necessarily greater than those of early Greece; they are likely to be inferior; and, of course, our men of science are not necessarily more intelligent than those of old; yet one thing is certain, their knowledge is at once more extensive and more accurate. The acquisition and system-

ization of positive knowledge is the only human activity that is truly cumulative and progressive."

This remarkable attribute of science is bought at a price, namely, the strict limitation of the subject matter. Science deals only with judgments concerning which it is possible to obtain universal agreement. These data are not individual events, but the invariable associations of events or properties which are known as the laws of science. Agreement is secured by observation and experiment—an impersonal court of appeal to which men of all races and all religions must submit if they wish to survive. We were not with Newton when one particular apple fell, but we all agree that apples do fall, and we conduct ourselves accordingly.

The laws of science are the permanent contributions to knowledge—the individual pieces which are fitted together in an attempt to form a picture of the physical universe in action. As the pieces fall into place, we often catch glimpses of emerging patterns, called theories; they set us searching for the missing pieces that will fill in the gaps and complete the patterns. We are constantly guessing at patterns of ever increasing generality. These theories, these provisional interpretations of the data in hand, are mere working hypotheses, and they are treated with scant respect until they can be tested by new pieces of the puzzle.

The formulation of a working hypothesis to account for data already available is definitely an ex post facto procedure—it gives a plausible, but not always a necessary, interpretation of the data. The essence of the scientific method lies in the testing of theories by new data, and especially by data in new fields. The validity of

theories is measured by the verification of predictions. When theories cannot be tested, their appeal is largely aesthetic.

No theory is sacred. When a theory fails to meet the test of verified predictions, it is modified to include the larger field, or, very rarely, it may be abandoned completely. Such changes are always welcomed because they represent a closer approximation toward the final picture.

Let me summarize this brief discussion of science. The subject matter consists of judgments on which universal agreement can be obtained by observation and experiment. The method consists of the interpretation of available data by working hypotheses whose implications are tested by further experimentation. Throughout the process, science is concerned with knowledge that can be freely transmitted, knowledge that comes from observation and experiment.

Such knowledge has two characteristics. In the first place, it is empirical. It has no direct contact with ultimate reality; it represents the physical world as the world appears to men. In the second place, it is probable knowledge; it never attains absolute precision. The scientist explores the world of phenomena by successive approximations. He knows that his data are not precise and that his theories must always be tested. It is quite natural that he tends to develop a healthy skepticism, a suspended judgment, and a disciplined imagination.

The general principles of the method are not peculiar to pure science. They are obvious in perfected disciplines such as astronomy and physics, but they are present in all attempts to ascertain objective truths. Success in those attempts is measured by the degree to which per-

sonal desires are suppressed, and by the amount of significant data that can be isolated—i.e., the data must be sufficient to indicate the correct pattern.

The study of modern history, for instance, was revolutionized in the nineteenth century by the opening of national archives. The scientific method could then be applied with more freedom, because it was possible to rely upon the more or less impersonal record rather than upon the prejudiced memoirs.

But the historian is still dependent on remains that cannot be greatly enlarged. In this fact lie the limitations of his discipline. The interpretation of any given set of data is, I repeat, an ex post facto procedure. Ingenious men can, and do, devise various plausible interpretations of the same set of data. Fifty years ago Froude remarked that "facts of history are like the letters of the alphabet—you may make them spell what you like." The most convincing method of discrimination would be the testing of implications of the different theories in fields previously unconsidered. The procedure is followed, of course, wherever possible, but the opportunities for the historian are far fewer than those offered in the laboratory.

I have spoken with confidence of knowledge because it is a subject on which we are all more or less informed, and we use a common language. Of the wisdom that comes from experience, I speak with diffidence, merely inviting your attention to the nature of the subject. We are steadily accumulating knowledge, and yet we know that we can never develop a culture out of knowledge alone.

We may say, with the usual reservations, that the realm of science, the objective world of nature, is ruled by necessity—apples fall, regardless of our desires. The world

of culture, on the other hand, is a world of choice. Right living, good taste, and good breeding—these depend largely on our own decisions, and, within limits, we exercise some freedom of choice.

Not only does man test the universe, but also the universe is testing man. From the moment of our birth, we are exposed to impacts on our senses from the external world; from their continuity, their variety, their richness, we gather experience. And it is from the multiplicity of all sorts of experiences that we gradually learn to make comparisons for ourselves, to know what we admire and strive for and what we disregard as unimportant. I have always thought that the briefest illustration of values was supplied by Dr. Johnson. A man stated that, in his opinion, it was more important to dress a good dinner than to write a good poem. Dr. Johnson in his sledgehammer style, replied, "And in that opinion, Sir, all the dogs of the town will join you."

If all men were alike, wisdom could doubtless be measured in terms of experience. But that is not the case. Some learn rapidly; others, it would seem, never learn. We know far too little of human nature to understand the process. About the only criterion available is the verdict of time. By and large, the years bring wisdom.

The urge for pure science is itself a value. As one aspect of the search for truth, science has a necessary place in any proper culture. This fact has not always been recognized. The old humanism, enshrined in the classical education of the last century, disregarded science. That education, as Barry described it, "was not the study of the great world of nature, but the study of man alone; and the study of man, not as the product and plaything of nature, but as a free immortal soul; and no longer a

struggling, humble soul, working its blind way toward the light, but as an ardent soul, whose thought was more interesting than his work, and whose love and play and dreams and songs, were more important than his thoughts."

The student was made familiar with the finest creative efforts of the race. The goal was good breeding—primarily a moral criterion, one which embodied the highest ethical and aesthetic ideals of the pagan and Christian traditions. Those ideals we must always cherish, or reject the instinctive wisdom of the centuries. They are, however, ideals of worth and of conduct, and they do not completely satisfy our needs.

Humanism, like science, is necessary but not sufficient for a proper culture. One man has said that he does not know which is poorer, the old humanist who does not recognize the cultural value of science, or the young scientist who lacks appreciation of beauty, of urbanity, and of reverence.

Today we strive for the larger view. Whereas a century after Newton, Pope wrote:

> Judge then thyself. Presume not God to scan.
> The proper study of mankind is man,

we believe today that the proper study of mankind is the universe, of which man is a part. We must explore both the realm of science and the world of values. For we believe that wisdom without knowledge is futile, and we know that knowledge without wisdom is dangerous.

This remark might well terminate a discussion of the experimental method, so conspicuous in pure research, and the formulation of values, so apparent in personal judgments. But before concluding, I wish to mention very briefly another aspect of the subject. In the world of

values, where universal agreement cannot be obtained, we may form our own judgments, but we cannot lead our own lives. The fact that we are members of a society necessarily introduces conflicts of desires and restricts complete freedom of action. Society provides protection and permits an organizaton of efforts which adds immeasurably to our material comforts and conveniences and to our leisure. In return, the individual must conduct himself with due regard for his fellows. Many of the rules of conduct, such as courtesy and generosity, are treated as private values; they are instilled in the home and are supported by moral sanctions. Others, more objective, are matters of state. They are determined by majority votes and are sanctioned by force and by economic pressure. Consequently, there is an ever-current problem of the relation between majorities and minorities.

Your generation has its problems in the field of politics and economics and sociology. Some of them are already formulated. Today, for instance, there is a definite trend in the direction of the totalitarian state. You will decide whether or not the trend should be followed to its dubious goal. Suppression of minorities, regimentation, uniformity of thought and action—these may have their uses in national emergencies such as war, but are they desirable in times of peace? Is it not preferable, in a civilized society, to encourage discussion of the common good from many different points of view?

In the field of economics, a minor revolution seems to be under way. After steadily rising since beyond the memory of our fathers, the trend in the price of raw commodities seems to have turned. Authoritative investigations lead to the conclusion that, very probably, the trend is now downward, and has been downward for several

years. The conclusion holds regardless of how the price is measured, whether by the old gold standard, by wages, or by the cost of the finished commodities. It seems that the means of production, which is a problem of applied science, has been increasing faster than the consumption, which is partly a question of human preferences.

If the change in the secular trend is real, as I suppose it is, you must accept it as a condition. It is not amenable to governmental experiments, to trade cartels or inflation. It may force radical readjustments in the world of industry, some of them very difficult indeed. But if the situation is handled wisely, and the political element does not get entirely out of hand, it may eventually result in a general elevation of the standard of living.

Other problems need not be mentioned, because I do not venture to propose solutions. I merely wish to emphasize what I believe to be the proper approach to questions. The problems of society involve human values as well as positive knowledge, subjective as well as objective judgments. Now it is a curious fact that we are most certain about judgments that cannot be demonstrated. Subjective certainty is inversely proportional to objective certainty. Russell put the situation rather bluntly: "Who ever heard a theologian preface his creed, or a politician conclude his speech with an estimate of the probable error of his opinion?" In these problems of society we are always tempted to rationalize and propagandize, rather than to investigate and discuss.

The introduction of human preferences and human behavior renders the problems desperately complicated. Many of the data seem arbitrary. They suggest a calculus of arbitrary functions, a logic of many valued truths. They even suggest an uncertainty principle. For, al-

though the behavior of individuals seems unpredictable, there is reason to believe that the behavior of groups tends to follow general patterns.

When you consider these present-day questions, I earnestly recommend the historical point of view. Proposed solutions of social and economic problems are derived from theories which only rarely can be tested by controlled experiments that really isolate the questions at issue. Yet, in a sense, history is one long record of experiments. Although history may never repeat itself in detail, general situations of a given character have arisen time after time. Consequently, it is possible, in a sense, to test the proposals by comparing their implications with the actual experience of mankind.

The procedure is so orthodox with sound students that it should be unnecessary to stress its desirability. Nevertheless, it is quite out of fashion with many who are attempting to direct the societies of today. Their attitude seems to be that the old order worked badly in spots, therefore they will throw it out completely, the good with the bad, and try something different. Well, they should at least make sure that their different proposals have not been tried and found wanting in the past.

The effects of such investigations, if they were made sincerely, would be interesting. My friends in the field of history tell me that both radicals and tories are extremely rare among the first-rate historians of the world. The leaders follow the middle way; almost to a man, they are classed among the liberal conservatives. Since, as I presume, their philosophy is the result rather than the cause of their unbiased examination of the experience of mankind, the fact is worthy of thoughtful consideration.

I should like to end on this note of history. It is a com-

mon meeting ground of knowledge and wisdom, of experiment and experience. It introduces and fuses the old humanism and the new science. And we need the combination. Once it was necessary to exhort the humanist to learn the cultural values of science. Now it seems necessary to urge the scientist to learn the values of humanism.

Sarton pictured the young physicist working quietly in the laboratory, undisturbed by the noise and clamor of a feverish world. He may know well enough what he is doing, but is he sufficiently aware of the multitudinous activities of his fellow men? The cure is found in the study of history, in the contemplation of the past. Let us, said Sarton, lift up to his eyes the great mirror of history, and urge him to use it as a mirror not of himself but of the whole of mankind.

PART II

"O'ER THE RAMPARTS WE WATCH"

It is an honor to address the Legion at any time, and especially today. For today the privilege carries grave responsibilities. Once again the Germans are on the march. They have plainly stated that democracies must perish from the earth. They are rapidly isolating the nations and stamping them out one by one. Our country, they reserve for the final push—and will we kindly keep quiet until the others are smashed.

Our answer should be plain. We must make sure and doubly sure that the Nazis are defeated while they are still far from our shores. And what are we doing? We are watching from our ramparts, while others are fighting to stem that rising tide of conquest.

The dangers around us are real and deadly. But the greatest danger is our complacency. The little aid we send to Britain, our modest efforts to improve defense, do these frighten Hitler? They are not enough. We are wasting time that waits for no man. Someone has said, "Better a Bolshevik who kills Germans than a Democracy that kills time."

I wish to discuss these matters with you. The subject is appropriate for old soldiers to discuss among themselves on the anniversary of the day that broke the might of the old Germany.

Let us recall those days for a while. Germany made her bid for conquest, and, as Wellington said of Waterloo, it was a damn near thing.

We in America sat on the sidelines and watched the show as though it were some sporting event. It took us two and a half years, and the threat of a German victory, to realize what the shooting was all about. Then, of course, when finally we did understand what a German victory would mean to our country, we stopped talking and we acted.

It was late when we declared war, but with the tremendous drive of a war spirit, we achieved national unity overnight and set about the job that had to be done. Of course we paid a high price for our procrastination. We did the job the hard and costly way, with great waste, much blundering and some stupidity—but we did it.

You will recall how hastily the army was assembled; how it was thrown into action, half-trained and unprepared; how we began to learn our jobs practically under fire. Our full efforts, you will recall, were scheduled for 1919. But because we did not hesitate, because we jumped in boldly while the Allies were still fighting hard, we swung the balance, and Germany collapsed on that memorable day just twenty-three years ago.

We were a part of all that, and we are quietly proud that we were there. We brought home some experience, some knowledge, and a little wisdom. We know what war is like—Sherman had the word for it—but we also know that war is not the worst calamity that can befall a nation. Peace at any price is a religion of slaves, and we are not tarred with that brush.

Let us never again forget this principle, as we did after the armistice when we relaxed and let the isolationists lose

the peace. We were told we were fighting a war to preserve democracy—and it was true. Democracy was preserved for a generation. We were also told we were fighting a war to end all wars, and it might have been true. But it wasn't; the isolationists saw to that, as soon as the shooting stopped and they dared to raise their heads again.

You know the sad story of the League of Nations, how the isolationist senators forced us to repudiate our own creation. Most people now agree that the League might have saved the peace of the world and prevented the rise of any Hitler. But without us, the League was doomed at its birth.

A friend was telling me the other night how he walked into the empty council chamber where the first session of the League was to take place. Along a table were placed chairs, with the names of the heads of all the delegations, from England and France and all the democratic world. In the very center was a larger chair, with no name before it, and my friend asked for whom that chair was reserved. For the delegate of the United States, he was sadly told. And all through the session, and through other sessions, there stood in mute, well-merited reproach to our country —the empty chair.

We soldiers can look facts in the face and not mince words when we discuss them. Some of you remember how, after the armistice, the French insisted on the left bank of the Rhine, as a guarantee against invasion by the next generation of Germans. President Wilson said no, it meant annexing German populations. There was an ugly deadlock which Wilson forced by signing a treaty pledging the faith of the United States to give armed help to France in case of attack by Germany. Relying on that faith, France released the strategic river with its bridge-

heads, and, as she feared, was invaded a generation later. For the isolationist senators in Washington repudiated the faith to which the President had pledged his country. And they acted too late for the French to get back the Rhine line that might have saved her in 1940.

We know that our treaties are not binding unless they are ratified by the Senate. Yet that answer does not really satisfy our private sense of honor. Moreover, in a practical sense, we lost the confidence of the world, and confidence is a tender plant, easily bruised and very slow to grow. When we justly criticise the other nations, let us not forget the poor example we ourselves have set.

So we won the war and lost the peace. And now, a generation later, the significance of that loss is forced upon us. We might call it destiny, for opportunity seldom knocks twice, and yet we hear it today, a martial drumbeat in the form of grim necessity. Once again we must insure the preservation of our democracy but, in the process, we are given the opportunity of correcting the tragic errors of the past.

History is repeating itself with painful fidelity. Germany took full advantage of our carelessness. What we neglected to do for peace and security, the Germans did for purposes of conquest—they stressed the *duties* of citizenship as well as the *rights*. And once again, Germany, powerful, efficient, and completely ruthless, has struck for world dominion. Once again it is a "damn near thing." Once again the war enters its third year while we watch from our ramparts and kill time. What about this third year? Will we, with all our experience, let the analogy stop there?

I need not repeat the old arguments; you know them too well. Hitler has flatly declared that he will wipe de-

mocracy from the face of the earth. He has the power to do just that unless we stop him soon. He dreams of world dominion by a superior race. Men of the Legion, we found the Germans hard, tough fighters, but did we find them a superior race? And they seem to have other dreams. Rauschning reports Hitler's conversations with his intimates. Concerning America, I quote: "The American is no soldier. The decadence and inferiority of this allegedly new world is evident in its military inefficiency. . . . I guarantee that a new America will arise as our strongest supporters when we are ready to take the stride into overseas space. . . . There will be no new Wilson arising to stir up the country against us."

Do you remember the story of Ulysses when he and his shipmates were captured by the one-eyed giant Polyphemus and kept in a cave? Polyphemus ate two men every night but he promised Ulysses, as a special favor, that he would eat him last. What did Ulysses do? He did not retire in a corner and take setting-up exercises. He was not an isolationist. Instead, he led his comrades in ganging up on Polyphemus, disabled the evil giant, and thus broke out into the light of day.

We know the military might of Hitler's Germany, we know Hitler's intention. What are we waiting for? No true American can any longer talk of appeasement or negotiation, the Nazi record is too plain and too evil for such idle speculation. And we cannot gamble on the chances of a German defeat at the hands of other nations.

Our choice is restricted to isolation or intervention, but because we are not contemplating suicide, it must be *heavily armed* isolation or *effective* intervention. If we look frankly at the staggering cost, the humiliation and the misery of life in an armed fortress for an indefinite

period, there is no real choice. Shall we and our children look out at the world through iron bars?

You remember your tactical walks. Let Sergeant Brown estimate the situation. He is a soldier, and will not indulge in wishful thinking.

Suppose that England and Russia, despairing of sufficient aid, should collapse. Africa and Asia follow as a matter of course. Then South America crumbles from within, nation after nation hurrying to salute the conqueror. Let us have no illusions over South America. That continent is at once a challenge and an invitation to a victorious Hitler. They listen to our speeches, yes, but it is our actions they watch and carefully appraise. If we should let England down, can you doubt they would turn to the Nazi? As my friend Balderston puts it, "Twenty-four hours after the elite guard goose-steps up Constitution Hill in London, South America goes Nazi. It is as simple as that."

And there is a path of conquest. An ominous wave creeping on toward the Mexican border, while to the north lies a dominion bitter and contemptuous. We would be completely isolated in a hostile world, quarantined in an armed fortress, striving painfully for self-sufficiency, with no foreign trade and a large fraction of our national efforts, billions upon billions of annual income, necessarily sacrificed to our defense. Under such conditions, our standard of living would fall to record depths. Our daily life would be regimented beyond anything we have ever experienced or imagined. In no other way could we survive as a nation. We would sacrifice our liberties for the emergency, and the emergency would be perpetual. Constant vigilance would be the price of security. Let that vigilance relax, let the subversive elements get out of

hand, and we would be ripe for invasion. Life in an armed fortress is not a good life, and it is not our democratic way of life.

This grim prospect is merely the logical consequence of the doctrine of isolationism. Such a course would be far, far more costly than outright war; it would be deeply humiliating and always dangerous. We cannot condemn our children to such a future. So let us once and for all have done with such talk.

No nation has ever succeeded in practicing strict isolation in the modern world. Japan tried it, and we ourselves talked her out of it. In a different way, some of the nations of Europe tried to keep apart, and you know their fate. Our Monroe Doctrine came into being and operated under the protection of the British fleet. We may not like to admit the fact but the record is clear. Our nation reached its maturity behind that front line.

Three times in the history of our union, European dictators have set forth on the road to conquest. The threat of Napoleon's bid was fully recognized. Jefferson was perhaps the most isolationist of all our presidents, and had himself drafted our declaration of independence from England. Yet Jefferson flatly stated to our agent in France, that, if it were necessary in order to insure Napoleon's fall, we should "marry the British fleet and nation." But Moscow and Leipzig and Waterloo intervened, and there was no need for this marriage of convenience.

Then the Kaiser tried his hand, and our response is the occasion for the anniversary we commemorate today. Now Hitler makes the strongest bid of all, and again we must intervene effectively—that is by all-out war. I am not suggesting that we should fight Hitler because we share responsibility for his success to date. I am not telling you

that we should fight England's war, or Russia's war. I am telling you that this is *our* war, that our miscalled aid to Britain is aid to ourselves and never was anything else.

I reached these conclusions eighteen months ago, and joined with others in calling for an outright declaration of war. Because the reasons are simple and just as valid today as they were when France was invaded, I will briefly summarize them.

We stand in the path of a conqueror and we are not prepared to meet the onslaught now and alone. A defense program is a race against time. The time must be secured at any cost, and every moment used to maximum advantage. Aid to Britain gives us time; we must use it well. The program is not primarily a question of money—it calls for discipline, for militaristic economy, and chiefly it calls for sacrifice. It calls for a supreme national effort in which politics are suppressed, controversies deferred, subversive activities stamped out. Such an effort has never yet been achieved in the peacetime organization of a democracy. I think it never will be so achieved, and even if I am wrong, it is reckless to gamble on the off-chance that this time it will be different. We must make the tremendous effort of a unified nation whose eyes are on a single goal—the destruction of Hitler. We must declare war.

Hitler, of course, did not and does not welcome a declaration of war. He hopes to keep us officially out until his European business is finished. He knows that our efforts will be multiplied overnight, and he knows the tremendous impact on the morale of friends and foes alike. He is fully aware of the anniversary we celebrate today. The wild surge of morale through the fighting allies, the wave of hope through the enslaved nations, the utter discouragement of the older German people—the effects of

these intangibles are beyond calculation. If we declare war today, the Germans know they are licked in the end, and our job shrinks by the very fact of taking it on. Do not misunderstand. We must face a long, tough, bitter war, but the sooner we start, the less terrible the price.

At the moment, what are we doing? Not enough. Some aid to Britain, some defense work, large promises for 1943 —jam tomorrow. Not today—we are too busy with our private concerns, cashing in on the emergency, social gains, closed shops, and all the rest.

Of course, we know that England and Germany and even Japan are giving more than half their productive efforts to the war—four or five or six hours each day. But what of it, we seem to say. Watch us tomorrow or maybe the day after. Why, after only eighteen months we are already spending one whole hour every day—that is, if we include our aid to Britain. In another couple of years or so we may even double that. Then we will flood Britain with supplies, and she will doubtless win the war for us.

Men of the Legion, these are half measures. They do not represent the behavior of a proud nation, facing a deadly menace with clear vision and steadfast courage. Such a nation would drop at once every unnecessary private activity; it would arm as speedily as humanly possible, seek out the source of the danger and destroy it, using every appropriate weapon and every convenient alliance. Well, why aren't we about it? What is holding us back?

We know what war is like. This nation was created by war, it was enlarged by war, it was preserved by war. Whenever our national existence is in danger, we must, and we will, fight again. That time is come—it is now, today.

Some timid souls ask plaintively, "But what would the boys fight with?" You know the answer to that one. Lack of equipment didn't stop us from declaring war; it was the declaration that produced the equipment, in record time —and that is one of the most important reasons for a declaration today. Moreover, we have trained pilots, skilled specialists, the all-important industry, and the greatest navy in the world, fully equipped. Japan cannot immobilize the whole of that navy. Our contributions for some time would consist largely of production and the delivery of most of the products to the firing lines abroad, where they can be used to immediate advantage.

As to "sending our boys to die in foreign lands," the answer to that one is also clear. If an A.E.F. is necessary to insure the destruction of the Nazi, then an A.E.F. must go abroad. It won't be a matter of choice, it will be a grim necessity. We cannot set limitations on our freedom. We cannot say that liberty is worth just so much and no more —so many ships, so many destroyers, so many lives. Liberty is worth whatever the price that must be paid. That was the faith of our fathers, and because of their faith, we are free Americans today.

And as for the "boys," well, we were "boys"—we called ourselves soldiers, and I suspect the new army does the same—and how did we respond to that great adventure? Were there any AWOL in your outfits when the ships pulled out? There weren't any in mine, but I do recall the howls of good men left behind as instructors.

I do not know the state of the morale in the army today but I am confident that whatever minor difficulties there may be will straighten out fast once war is declared. As Knickerbocker says, what can you expect in a football team practicing with a tennis ball, and no games sched-

uled? I doubt if we would have done any better under such circumstances.

The navy has the jump on us. They are already in a shooting war. They have seen their dead, and they have thrown away their blanks—it's ball cartridges now. But for the rest of us, we are running all the risks of war, and reaping none of the advantages.

Men of the Legion, you speak with authority; you have already backed the foreign policy, in principle. I urge you to take the last, necessary step; I urge you to call for an outright declaration of war. Think it over now, tonight, tomorrow, but not too long. The arguments are all in, and the decision is long overdue.

Step into the future; regard our present situation in the light of history. How would we tell the story to a stranger, say from another world? We would tell him the all-too-familiar tale of the plans laid by Hitler and his Nazis—plans openly announced and carried out successfully, one after the other, on schedule; of promises and treaties made to be broken; of a nation turned into predatory beasts, flouting all other men's rights to liberty and life; of neutral countries invaded without warning, ruined, enslaved, their peoples slaughtered, their lands laid waste; of all that civilization has stood for, going down into the darkness as the menace crept nearer and nearer to us.

And what did you do, the stranger will ask. Must we answer that we took half measures? Looked at historically, our conduct would be incredible to anyone but an ostrich.

Unless we deliberately choose to be blind and deaf, surely we have no need any longer to go on reciting the lists of our perils, to go on discussing them with an aca-

demic sort of futility. We are confronted with the necessity for a world crusade against the greatest danger that has ever imperiled the decent progress of society. If we do not, at this eleventh hour, recognize the imminence of the emergency, we shall deserve whatever we may get. Shall we continue to watch from afar while brave men defend our lives and liberties as though we were a lot of women and children? If they lose, what will we say for ourselves? If they win, with what countenance do we receive from their hands the benefits of liberty, safety and life itself? Our material position may be all that we might hope, but shall we be completely comfortable in it?

Are we, our "native hue of resolution," like Hamlet's, "sicklied o'er with the pale cast of thought," to watch from behind our ramparts while others fight the common enemy? If so, one phrase of our national anthem will be forever true of us. When we sing the *Star-Spangled Banner*, we will truthfully sing "O'er the ramparts we watched."

Would it not be a more glorious page of our history if we could write our version of the lines from Henry V—when at Agincourt, on that St. Crispin's day five centuries ago, Henry tells his men that never an anniversary will come

> From this day until the ending of the world
> But we in it shall be remembered.
> And gentlemen in England now abed
> Will think themselves accurst they were not here,
> And hold their manhoods cheap whiles any speak
> Who fought with us upon St. Crispin's day.

This war is our war. The final stake is our freedom and the freedom of our children. Let us never forget that this freedom, this liberty, is the heritage of brave men who, the world over, since time began, have fought to achieve and maintain it.

THE SCIENTIST AT WAR

If you read Voltaire, you will recall that Candide, after his adventures in the world of human affairs, was content to retire and cultivate his garden. In much the same spirit, the scientists of our day are contemplating their gardens. They too have had their adventures in the world of human affairs, and they are returning with relief. The gardens need cultivating. There was little or no real progress in science during the war, except perhaps in the fields of medicine and surgery. The research men are returning to find the same old problems just about as they were left.

Science acquires knowledge but has no interest in its practical applications. The applications are the work of engineers. The war effort was a triumph of engineering, of the practical applications of knowledge already available. Scientists were called out to work as and with engineers. In the first place, there simply were not enough engineers to meet the emergency, and scientists had the basic knowledge, even if they did not have experience in the applications.

In the second place, engineers do not keep up to date. They use knowledge only when it is thoroughly seasoned and even familiar. During the war, efforts were made to tap the reserve of raw, unseasoned knowledge available in the laboratories, and the scientists were the only men who knew its full significance and implications. What the scientists did in this war concerning the atomic bomb,

for instance, the engineer would have done in the next war. Many of the scientists proved themselves adequate, and some of them did truly remarkable jobs. However, it should be emphasized that they were operating not in the field of science, but in the field of engineering.

My own adventures lay in the field of ballistics. It came about as follows. Some time after Pearl Harbor, while I was trying to get back into the infantry, I was called in by Army Ordnance, and told, in effect, to stop that nonsense, that I had been earmarked long before for a job in Ordnance and would I please get onto it. The job—they called it a "mission"—was to take over Exterior Ballistics at the Research and Development Center of the Ordnance Department, located at Aberdeen, Maryland, on the shores of Chesapeake Bay. Using the customary formulae, they insisted that the "mission was important and urgent and affected the immediate conduct of the war," and if I had any doubts I was to go at once to Aberdeen and investigate for myself.

Well, my first reaction was, I think, just about what yours would have been. I rushed to a dictionary. Ballistics, it seemed, was the science of hurling missiles against an enemy. That seemed a trifle thin so I turned to the encyclopedia. There I found a long article, but it puzzled me. Ballistics was evidently either undeveloped or highly classified. So I went to Aberdeen, partly to find out. I found out. Ballistics was both underdeveloped and overclassified. For instance, the performance of a newly designed shell could not be predicted from the drawings and specifications. If they resembled those of a shell that had been tested last year in Oklahoma, we guessed the new shell might behave in much the same way.

A few first-rate scientists with proper support could

systematize the subject in a relatively short time. But that isn't the way our country faces its obligations. We start each war with the weapons used at the end of the previous war. In between, when we should concentrate on research and development, we just can't be bothered. I asked the generals why, and they murmured "appropriations." But the Chairman of the House Military Affairs Committee, when I asked him why, told me that as far back as he could recall, the committee had never disapproved a single request for funds for research and development—the requests just hadn't been made. Actually, as I found out, the generals are not entirely to blame. The Director of the Budget takes a hand and, after a good deal of squabbling, the Chief of Ordnance goes to the committee (as I guess, without knowing) under orders as to how much he requests.

At any rate, the army seems to feel they can't justify research during peace, and, of course, they haven't the time during war. This situation led to many grimly amusing incidents. The army would come to us with an urgent problem that had arisen in the actual fighting. I would have to say, "We don't know, but of course we can find out." "Go ahead, find out," the army would say. "All right. It will take so many men, so much equipment, so much time if we stop other work, and give it priority." "Time," the army would say, "hell, we have to cable the answer tonight." Then we would demand to know why the necessary investigations hadn't been made before the war so that reasonable answers could be given on a moment's notice. In the end the army would admit that somebody had to guess and we, they believed, could guess better than they. It wasn't altogether a matter of passing the buck, it seemed to be an honest attempt to do the best

that could be done under the circumstances. But what circumstances.

To get back to ballistics, the center of the Aberdeen establishment was a Ballistic Research Laboratory which had a small staff in peacetime and was suddenly called upon to carry an enormous load of work. There was a thoroughly competent regular army officer, Colonel Simon, acting as director, and one outstanding staff member, Robert Kent, who is the equal of any ballistician in the world. Kent, by the way, had once presented a thesis on ballistics for a Ph.D. at Harvard. It had been turned down, although it is recognized today as one of the very few fundamental authoritative contributions in the field. He went with the army, a student rather than an administrator, and in spite of the obstacles, became the recognized leader in the country. I tell this story as a commentary on the status of ballistics in America.

The subject is not studied outside the armed forces, and not too widely within. So, when the need for expansion could be foreseen, there was no reservoir from which to recruit. All that could be done was to call on research men from other fields in the hope that they might "mug up" the new subject somewhat faster than laymen. Simon and Kent called for advice from scientists in the east, mostly National Academy men, and made a list of possible victims against the day of need. My name, they told me, was top of the list because ballistics has a curious affinity with astronomy, and, moreover, as a line officer in the last war I might appreciate the significance of some of the problem as viewed from positions in front of the guns as well as behind the guns.

These men explained the whole situation to me—the obstacles and frustrations, as well as the really desperate

needs and the opportunities to contribute directly to combat problems. They also brought in the generals, as a sort of window dressing. They stressed the needs and not the obstacles, and promised full backing. And they gave it—especially General Levin Campbell, Chief of Ordnance, who became a stanch supporter in some difficult situations. For I joined the group largely because the need was so apparent, and there were no candidates especially qualified for the work.

Then we settled down to work. Ballistics is divided into three parts: interior, exterior, and terminal. Kent took over Interior Ballistics—guns, propellant powers, all the phenomena inside the gun, erosion, recoil, etc. I took Exterior Ballistics—following the projectile from the launching to impact or burst; and eventually Joe Mayer of Columbia took Terminal Ballistics—armor penetration, fragmentation, blast phenomena, and the like.

Exterior Ballistics had three major problems to start with. First, it was responsible for all the firing and bombing tables used in the army. The importance of this work may be guessed when you picture a bomb released three miles ahead of the target or an anti-aircraft gun firing at a plane. New tables were required not only for each new gun, shell or bomb, but for each modification of those already in use, and for captured enemy materiel.

The pressure for tables was enormous and we set up a special group under a man who devised computational methods in the last war, and was now a professor of mathematics at Brown University. He ran out several dozen tables each month with the help of about 150 computers, two of the four differential analyzers in the country, and a large collection of I.B.M. punch card machines. Once this production unit was in operation, I took no part in

the routine work. But all new weapons were funneled through us. We studied the actual performance in the field, devised procedures for making tables, and actually calculated the first samples. Thereafter the production group took over.

The second problem was to assemble basic data for the design of new projectiles, which should have been done in peace times; the third was to provide cam data for fire control instruments and bombsights. We became specialists in bombsights. They are complicated computing machines, but they cannot take all variables involved in the bombing problem. Consequently, it is necessary to use combinations of variables as single units, and the choice of practical combinations requires a broad background of theory and experience.

This was the picture as it first appeared. We thought we would do basic work, and the results would be for general use. For instance, assemble basic data for design of shells, but let the engineers actually design the shells required for the special purposes requesting the using service. But it didn't work out that way. We became trouble shooters and did service work on special problems. The work had to be done and there were no other competent organizations available.

The greatest difficulty arose from the fact that, with the full backing of the Ordnance Department, I had developed research facilities which gave high accuracy but at the price of time consumed. These facilities were diverted, under pressure, from research to service work in which speed should have been sought at the expense of accuracy. The delays led to some grumbling, but Ordnance accepted the situation, realizing that we were using research tools to pinch hit for service facilities they should

have provided elsewhere. They deplored delays, but bragged about the precision and reliability of results when they were sent forward. Meanwhile, they called on us for a lot of guesswork, because "somebody had to guess."

Exterior Ballistics developed into so large a department that it dominated the Ballistic Laboratory. In its final form there were about 280 in the department, about equally divided between civilians, officers and enlisted men, and WACs. The WACs were a godsend, because they were selected from college graduates in mathematics and physical sciences, and came at a time when it was extremely difficult to find civilians. The enlisted men were selected from advanced ASTP students and included various Ph.D.'s. It was so difficult to get proper ratings assigned the group that we devised a slogan, "In the BRL, a PFC is a Ph.D."

The department consisted of five units: a theory group, two laboratory units, and two field units.

The theory group consisted of mathematicians, some of them topflight, surrounded by computer girls who had majored in mathematics. This group, under Edward J. McShane, completed for the first time the general theory of projectiles of all kinds. The theory described the motion through the resisting medium of the air, so long as the yawing is not excessive, taking into account all the forces and moments acting on the projectile. It is a contribution of first importance, and, if the effects of large yaws can ever be included, will close that chapter of ballistics. For the most part, however, the group spent their time trouble shooting (where the power of analysis developed by mathematicians was invaluable), in studying new weapons, and in critically examining bombsight designs and bombing techniques. One real feat was to pro-

duce bombing tables for Russian bombs without any data except qualitative descriptions. These tables were for the use of our bombers on their return trips when they started landing in Russian territory.

The laboratory units consisted of an indoor precision firing range and a supersonic wind tunnels laboratory. Here small models of shells and bombs were tested and studied. On the range, the flight characteristics were studied from photographs and measurements of models in actual flight. Twenty-five stations were scattered along the 100-yard range, at each of which shadow photographs in two planes were recorded by sparks lasting about one millionth of a second, tripped by the electrostatic charge on the projectile as it passed. Each station gave the orientation of the projectile, and, by collapsing the stations, the wobbling of the projectile could be measured and analyzed. Distances were measured to ¼ millimeter, and times of flight to about one millionth of a second.

The field units photographed and measured projectiles in flight out in the open, using straight astronomical techniques. The ballistic cameras were developed for stratosphere bombing. Units were installed in several parts of the country and the navy has also taken them over.

The Proving Ground Measuring Group worked on mortars, bombs, rockets, and especially on rockets and other projectiles fired from aircraft. The group operated with high-speed movie cameras which were accurately surveyed in, and synchronized so that times could be recorded to the nearest ten thousandth of a second. With a dozen such cameras on a program, it was possible to determine the position of the curve gradient of a rocket in flight to about 1½″ over a trajectory of ½ mile, at the

same time studying the behavior of the plane before and during the launching of the rocket.

This group also was headed by an astronomer, Professor Dirk Reuyl of Virginia, and it usually had several sections spread over the country, especially after it began using phototheodolites and synchronizing various airplane cameras.

It can be said that we developed the methods of precision measurement by photography, as far as they will be pushed. This is because the technique will be replaced sometime by radar and electronic gadgetry, which will be accurate and self-recording and hence will give the answers at once without waiting on the slow process of measurement and reduction of film.

Some typical problems will give you some picture of the operations. All-around machine-gun fire from aircraft was a difficult problem because when firing broadside, the terrific crosswinds of three to four hundred miles per hour introduced wild yawing. It was finally worked out with the aid of high-speed cameras in the plane as well as cameras on the ground. The bending of the gun barrels in the wind was a contributing factor in the problem.

Another tough job was the matching of machine-gun bullets for all-around fire. Tracers, incendiaries, and armor-piercing bullets were distributed along the ammunition belts, and it was necessary to adjust the charges so that the tracers actually did show where all the bullets were going.

We also worked out all-around firing of rockets. I recall the problem of a finned rocket launched to the rear from a 10-foot tube in the tail of a bomber. The rocket, on leaving the tube, had an absolute velocity about equal to the speed of the plane. Somebody had remarked that,

if the plane speeded up faster than the rocket, the rocket, on leaving the tube, would turn around and pursue the plane with increasing velocity. We had to assume then that the plane would probably be safe.

There were some exciting adventures with large rockets, guided missiles, and the giant grand-slam bombs, but they must wait awhile, along with the really hush-hush stuff.

This war ended on the note of guided missiles and atomic power, just as the last war ended on the note of aircraft. Consider the work of the Air Force in the present war, and then try to imagine the role of the new weapons in the next war.

It is possible any time after five years, and probable after ten, that any war between major powers will start with the mutual destruction of concentrated forces, industry, and cities, during the first week or so. Then, I presume, the real war will begin with the use of small units—commandos—and drag on to exhaustion.

At any rate the problem today is not that of controling the bomb—it is that of stopping war. War can be stopped when, and only when, we are ready to use physical sanction—when we are ready to use a police force bought at the price of a modicum of sovereignty. We may not like the price, but it is cheap for what we buy—civilization and life itself.

THE WAR THAT MUST NOT HAPPEN

Our age, for better and worse, is an age of technology. Technology is concerned with turning knowledge into action. The tremendous advance of technology during the past century has reduced the world to the effective dimensions once assigned to a single state. And the advance continues at ever increasing speed.

In this shrinking, jostling world, sovereign nations, uncontrolled by authority, compete for security, for wealth and for power. "He will take who has the power, and he will hold who can." Restraint is exercised only by war and the threat of war. Consequently, wars are normal episodes in the histories of all nations. And, as the world has shrunk, the scope of wars has spread until they now cover the globe.

Two great wars have been fought in our own generation, and the nations are now preparing for the next war. They have learned by bitter experience to prepare for the worst even while they hope for the best. The United Nations has been organized, but until its competence to maintain law and order has been demonstrated fully, we may well hesitate to place in its control the fate of our country. The other nations feel much as we do. Consequently, everyone is preparing for the next war, well knowing that when it comes, it will necessarily involve the entire world.

Let me mention very briefly some features of the next war, starting with the assumption that nations in a struggle for survival will use every resource at their command, and in particular they will use technology.

Scientists in their explorations have recently entered new fields, and in these have found knowledge of a quite new kind. Through technology, this knowledge is being used in a way that will convert war into suicide. The tremendous powers than can be unleashed can destroy whole civilizations in a matter of moments. There are no adequate defenses, nor do we see any likely prospects for their development. The best defense seems to be to attack first, although we in America would not want to adopt this plan of action.

If a war between major nations occurs at any time after, say, the next ten years, we may confidently expect each side to blast out the greater part of the other's material civilization within a brief period measured in hours. Then, presumably, will start the long dreary years of a war of exhaustion, a war of commando raids and small units, a war for brute survival in the shambles of a ruined world.

It is this unholy prospect, this logical consequence of new knowledge at the disposal of traditional politics, that is so profoundly disturbing. We have entered upon a new era—an era of great promise if we use the knowledge wisely, but an era of deadly danger if we are complacent and careless.

The last war ended with jet propulsion, long-range rockets, guided missiles and atomic bombs—a devastating combination. You have heard of them all, and, in addition, you have doubtless heard some references to the possibilities of bacteria and radioactivity. These things have

emerged from behind the veil of secrecy, and are openly discussed. What remains behind the veil, what is being developed, or can be developed with knowledge already available, must be left to your imagination.

I will not enlarge on the awful powers of the new weapons with which cities and populations can be destroyed as readily as individual houses and families were blown to bits in the last war. But I can assure you that scientists, engineers, and military men gloomily conclude that the picture of a "push button" war with the new weapons is not fantastic or inconsistent or improbable. It is the logical consequence of total war between nations fully prepared for a struggle for survival.

When one of the generals was asked just what weapons would be used in the next war, he replied that he could not predict because the development was too fast but, he said, he knew what weapons would be used in the war after the next—they would be clubs and spears.

Warfare with the new weapons will be the ruin of civilization as we know it. If you accept this thesis, and are interested in survival, you must accept the conclusion, namely, the absolute necessity of eliminating warfare.

The scientists are aware of the implications of increasing knowledge. They know it can be used for good or for evil, and their earnest prayer is that as knowledge increases, so also may wisdom increase. But they are all uneasy and some openly say they are badly frightened, and especially by the apparent refusal of politicians to face the issue, namely, the necessity of stopping wars completely.

The problem of stopping wars is the problem of enforcement of international agreements, a problem that has been with us throughout history. Treaties have been

made by the hundreds and by the thousands, but no adequate authority has ever been established to enforce the treaties. Performance has always been left to the wishes of the individual signers. Consequently, the breaking of treaties, and wars, have persisted as normal, recurrent episodes of international competition. They have been tragic, ugly episodes; but with fortitude, they have been bearable.

But now, in this age of technology, war is suicide. Politics and diplomacy have muddled along for generations, wavering about a general level, sometimes above average, sometimes below. Meanwhile, physical science, with technology in its wake, has swept forward with ever increasing speed. The danger level has been passed, the momentum is still increasing. The potential blessings of this new knowledge are enormous in terms of prolongation of life, surcease from pain, ease of living and leisure. But we shall not live to enjoy these blessings unless the military applications of the new knowledge are completely controlled—in other words, unless wars are stopped.

It does no good to outlaw major weapons by international agreement. Until the treaties can be enforced by some higher authority, we must not expect any combatant in a life and death struggle to fight with one hand tied behind him. There have been many such agreements forbidding, for instance, the use of submarines, the bombing of undefended cities, the slaughter of civilians. The history of such ventures is disillusioning. Even the one case sometimes offered as encouragement—that Germany did not use gas in the last war—cannot be traced to any regard for treaty obligations. Any authority with sufficient power to enforce agreements to outlaw weapons

could equally well enforce agreements to outlaw war itself.

The attempt to eliminate wars by treaty agreements has been tried over and over again, and it has always failed. History is largely the long unbroken record of its complete failure. Every war has started with a broken treaty. Yet today, when the abolition of war is not merely desirable but is absolutely imperative, our political leaders follow the old rut of demonstrated failure. They propose the same old procedures of treaty agreements. The United Nations is still based on treaty agreement. The politicians hope, as they have always hoped, that this time it may be different, that enlightened self-interest will serve as an adequate sanction. Can you doubt that these hopes are vain, that disillusionment will follow, as it always has followed? Can you doubt that these treaties will be broken as such treaties always have been broken, and that war will follow, with its inevitable consequences?

The performance of treaty obligations cannot be left to moral sanctions, any more than respect for traffic regulations can be left to the decency of motorists. Until human beings attain a higher level of development, performance can be insured only by an adequate police force.

This conclusion indicates the lines along which a solution to the problem of stopping wars must be sought. Actually, it suggests the only solution that we know, namely, a world authority armed with a police force. The essential features are that the authority, once established by agreements in the form of a constitution, will be above, and independent of, the individual nations, and will have sufficient power to maintain its position.

This solution was accepted on a smaller scale by our forefathers. The American colonies, when they broke away from England, became independent sovereign nations. At first they tried to operate as usual by treaty agreements, forming a confederation along the general lines proposed for the United Nations. When the system proved to be a failure, as it did quickly and inevitably, our forefathers had the wisdom to establish the United States of America, based upon a constitution supported by police power. A human mistake of underestimating the requirements of the police force was paid for by a costly civil war, but the Union has since justified the bold decisions of its founders.

A world government with a powerful police force, for the strictly limited purpose of preserving order among the nations, is generally considered as an ideal solution—a scheme that would certainly work if it could be initiated and kept alive for a critical period of adjustment. But, say the politicians, it cannot be initiated, at least not now.

Objections center about the sacrifice by the nations of some measure of sovereignty. In the atmosphere of lawless competition and mutual suspicion, the old question is raised as to who will police the policemen—*quis custodes custodet*. The answer, of course, is that which applies to the federal authorities in our own United States where all of us, through the ballot, police the policemen.

It is true that no element of national independence should ever be sacrificed carelessly or needlessly. But today, when the illusion of isolation is dispelled, when competition grows as the nations crowd together in the shrinking world—under these conditions, complete sovereignty leads to war and mutual suicide. Let us remember that it takes at least two parties to keep the peace. One

party can start a fight—two are required to avoid a fight.

Sacrifice of sovereignty has been the barrier to world organization in the past because the advantages of absolute sovereignty were believed to outweigh the ravages of war. Technology has made the argument invalid. War means mutual destruction, and all attempts to stop wars by treaties between sovereign states have been futile. There seems to be no choice. It is now world government or no world—one world or none.

A union of nations presents difficulties of the same kind as those which our fathers faced—and overcame. This time, the difficulties are greater. They also must be overcome, and when the politicians say it is impossible, their spirit is not the spirit that led our armies to win the war, and our scientists to make the bomb.

It is a fortunate and rare occurrence to find great men in times of emergency. But a democracy, if it survives, must be capable of functioning through mediocre men. To do this, two steps are necessary. There must be an informed public opinion, and it must be used to force the men elected by the citizens to action deemed necessary by the citizens. The responsibility rests upon each of us, upon everyone in this room.

It is no good listening to a talk, and leaving to resume our private affairs. The general public—and we are members of it—clings, through inertia, to the vague hope that someone else will assume the responsibility and see to it that nothing will happen. Or, under the impact of repeated warnings, we develop a sense of familiarity which, while nothing yet has happened, becomes indifference. And always we feel the difficulties of discriminating among various counsels, and of knowing what to believe.

For a time, much was said, much was written about the awful nature of the atomic bomb, and the shock of its devastating possibilities roused in us a sense of fear. But, concerned with our private affairs, we are inclined to ignore the menace. We are like the people who planted vineyards on the slopes of Mount Vesuvius, and lived brief, precarious lives under its sleeping threat. The menace is still here. And to the bomb must be added future, more deadly weapons.

Under these circumstances, I offer two suggestions. In the first place, we must have the energy, the determination, to inform ourselves as far as possible—to read widely and learn to discriminate between facts and falsehood, between wisdom and folly, between statesmanship and politics. For a beginning, I call to your attention two publications: *One World or None*, a pamphlet in which leading American scientists state the facts about the bomb, and *The Anatomy of Peace*, by Emory Reeves, which discusses the enforcement of treaty agreements. Let us get these things clear in our minds, and then let us, not as proselyters of propaganda but as citizens, try to influence other citizens in our own community and in widening circles to the sense of individual responsibility.

In the second place, we must choose proper representatives, and we must see to it that they know and carry out the will of the people who elected them. These are our individual responsibilities. They are not to be shirked or put off through what is our greatest weakness, namely, laziness of mind and will power.

Our position today resembles in some respects that of England and ourselves in the early thirties, when, if men had been vigilant and wise enough, World War II might have been forestalled. Let me quote a paragraph, a warn-

ing given, alas, in vain, and at how tragic a cost to us all, from a speech in 1935 of Winston Churchill.

When the situation was manageable it was neglected, and now that it is thoroughly out of hand, we apply too late the remedies which might have effected a cure. There is nothing new in the story. It is as old as the Sibylline Books. It falls into that long dismal catalogue of the fruitlessness of experience and the confirmed unteachableness of mankind. Want of foresight, unwillingness to act when action would be simple and effective, lack of clear thinking, confusion of counsel until the emergency comes, until self-preservation strikes its jarring gong—these are the features which constitute the endless repetition of history.

Now to summarize briefly in conclusion. The world today has become so small, so to speak, in the accessibility of all its regions, that it is no longer possible for any nation to achieve safety in isolation. We are all part of an organic whole, members of one body. Even if against our wishes, we must cooperate successfully in order to survive. There will be no defense from now on against attack. War and suicide—we must accept these as synonymous terms, for they amount to that. Yet this awful situation bears a challenge with it, and even a hope. Mankind is forced to make a choice which could lead from brute violence to a nobler level of existence.

Treaties are pieces of paper which can always be torn up, which have never proved a safeguard against the rapacity of a nation on the prowl for power. Let us not put our faith in treaties. If we can accept world federation with an international police force, as a goal to work toward, it is in itself a great step toward salvation in every sense—physical, economic, and spiritual.

World government for the maintenance of law and order is an ultimate goal of civilization. There has been

steady progress toward the goal. Families have combined into tribes, tribes into states, states into nations, and nations into empires—sometimes freely, sometimes under compulsion. The last step is desirable and inevitable, it is merely a question of timing. Once the step is taken, and such a world government has been in operation for a generation or so, it will be accepted as the reasonable way of life. Men will doubtless look back on these lawless days of blood and violence with the antiquarian interest that we feel in a lesser way towards the pioneer days of the West—the days when each man, with his gun, was a law unto himself.

I am well aware that the idea of world government is so strange that it seems enormously difficult. But we need not assume that we must accomplish everything at once, completely ready to function. What we should attempt is to accustom ourselves to it as a desirable philosophy that we can accept, read what men of intelligence are saying of it, discuss it, and, if we grasp its necessity, urge that our politicians also accept it—in a form general and elementary, but potentially ready to absorb such changes as experience may demand.

We would not, if it lies in our power, condone the destruction of our families, our cities, our country. How much the more should we exert every effort toward the preservation of the home of all living things, the very planet, the earth, which bears our destiny as a race. We are, whether we will or no, to take our parts in the making of cosmic history, a vast mysterious plan, one must admit, but there it is. Such action makes great demands upon us, of unselfishness, wisdom, humility, and human dignity.

But the actual step is a humanly difficult problem. We

are being forced into it by advancing technology, and many of us lack the vision to welcome it. Out of the peril of the bomb has come perhaps one good, and without a threat of this magnitude the human race might, for a long time to come, have blundered and stumbled, not admirably but with comparative safety, on its difficult road. We could say, like St. Augustine, yes, we will reform, we will be good, but tomorrow perhaps, not just yet.

Now, it appears we may not have a tomorrow. All at once we are confronted with the desperate necessity for decision and action. And in spite of whatever compromises, whatever postponements, our politicians or we ourselves may plead, it must be met.

Otherwise, we invite the war that must not happen: we invite destruction.